DEVELOPMENT OF A PERIODIC 10 K SORT'TION CRYOCOOLER

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ABSTRACT

The design and fabrication of a small, closed-cycle, periodic 10 K sorption cryocooler laboratory system is described. The cooler is designed to provide cooldown from 60 to < 10 K in under 2 minutes, maintain a simulated detector heat load of 100 mW below 10 K for over 10 minutes, and have the ability to be recycled in under 6 hours. A $LaNi_{4.8}Sn_{0.2}$ hydride sorbent bed is used to compress and circulate hydrogen refrigerant in the 24-30 K Joule-Thomson intermediate refrigeration stage. A ZrNi hydride sorbent bed is used to provide the low vacuum pressure (< 2 torr) needed to solidify and cool the hydrogen to 10 K. Thermally cycling the sorbent beds between 290 and 550 K produces a compression ratio of nearly 10^6. A vacuum-pumped liquid nitrogen loop is used to simulate a mechanical cooler or radiator for the upper 60-80 K stage. Performance predictions are presented, results are compared with ground test data from the flight-qualified Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE), and plans for using the cooler as a test bed for future reliability y physics experiments are described. Performance and reliability test results, combined with BETSCE flight validation data, will enable early insertion of this long-life (> 10 years), low-vibration refrigeration technology into precision-pointing military surveillance, earth-observation, and astrophysics space satellite applications.

INTRODUCTION

Recent advances in sorption cooler technology have shown a significant potential for the application of sorption coolers in a variety of areas[1,2]. Thermally powered sorption compressors with no moving mechanical parts have a fundamental advantage over conventional compressors due to their low vibration and potential for long-life reliability. Cryogenic applications for this technology include astrophysics, earth-observation, and military surveillance satellite systems. For those applications which require only intermittent or periodic cooling, sorption technology is

" particularly attractive due to its quick cooldown capability and its low average power consumption.

This paper describes a small, closed-cycle periodic 10K sorption cryocooler that is being developed to conduct performance and reliability studies. Test results are expected to lead to improved understanding and improved performance of both periodic and continuous 10- 25K sorption cooler.

Periodic 10K Sorption Cooler Concept

The concept of a periodic 10 K sorption cooler was originally developed by Johnson and Jones in 1990.[3][4] A simplified schematic of the 10K system is shown in Figure 1. The basic principal is to utilize metal hydride powders to compress and recirculate hydrogen gas within a closed-cycle Joule-Thomson system for periodic cooling of sensors at 10 K.

The cycle begins with the tank initially charged to approximately 10,3 MPA (1500 psia) with hydrogen gas and the cryostat upper stage maintained at a temperature of 60 - SO K. Cooling for the upper stage could be provided by a number of currently available Stirling, pulse-tube, or sorption coolers operating in the 60 K temperature range. For this particular cooler, liquid nitrogen near its triple point is used to obtain temperatures from 65 to 80 K.

When the command is given, a solenoid valve is opened, releasing hydrogen from the tank, through the JT loop of the cryostat, through a check valve, and into a $LaNi_{4.8}Sn_{0.2}$ hydride sorbent bed. Within the JT loop of the cryostat, the hydrogen gas is precooled and expanded, producing liquid hydrogen at the cold head. The $LaNi_{4.8}Sn_{0.2}$ hydride sorbent bed absorbs the in-coming hydrogen gas and maintains the vapor pressure of liquid produced in the coldhead between 24 to 30 K.

After enough liquid has been accumulated in the coldhead (typically 1 to 2 grams), the solenoid valve is closed, halting gas flow. Immediately, another solenoid valve is opened, exposing the coldhead to the low pressure ZrNi hydride sorbent bed. The ZrNi hydride absorbs the gaseous hydrogen in the coldhead, reducing the vapor pressure to below 266 Pa. This reduction in vapor pressure solidifies the liquid hydrogen and cools the coldhead to approximately 10 K. As the solid hydrogen sublimates due to the applied heat load, the low pressure sorbent bed maintains the temperature of the coldhead at 10 K by absorbing the sublimated gas. This temperature is maintained until the solid hydrogen is completely sublimated, or until the ZrNi hydride is entirely saturated.

To recharge the tank with hydrogen and prepare the system for another cooldown, the low pressure bed is first heated to a temperature of approximately 550K. This drives the hydrogen gas present in the ZrNi hydride from the low pressure bed at about 1.01 kPa, through a check valve, and into the high pressure bed where it is absorbed by the $LaNi_{4.8}Sn_{0.2}$ hydride. Next, the high pressure bed is heated to a temperature of approximately 545K. This releases hydrogen gas at about 10.3 MPA. The high pressure gas then flows through a check valve from the high pressure sorbent bed back into the tank. Once the sorbent beds have cooled back down to ambient temperature, the cycle is complete and the system is ready for the next cooldown operation.

JPL Sorption Cooler Development Program

A series of proof-of-principle experiments were conducted in 1991 which successfully demonstrated the key technologies of a 10 K sorption stages Based on the success of these experiments, the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) was developed as a spaceflight demonstration of the critical 10 K sorption technologies.' BETSCE is a space shuttle payload side-wall-mounted experiment which represents the first closed cycle

10 K sorption cryocooler ever built. Extensive ground testing of BETSCE has already been conducted, and the scheduled shuttle launch is set for April, 1996.

The periodic 10 K sorption cooler described in this paper represents the next step for the technology. In developing this new cooler, it was desired to produce a greatly simplified and compact laboratory version of BETSCE which would incorporate many of the lessons learned during ground testing of the spaceflight experiment. Important changes incorporated in this new design include the following: a greatly reduced size and mass, use of two rather than three sorbent beds, use of passive check valves as a replacement for active solenoid valves, and a completely redesigned Joule-Thomson expansion device, coldhead, and thermal storage device. In addition, the gas-gap heat switches for the sorbent beds were eliminated to simplify the laboratory cooler.

HARDWARE DESIGN

Off-the-shelf technology was incorporated into the cooler design whenever practical. Emphasis was placed on minimizing the size of the cooler while balancing the additional goals of facilitating fabrication and minimizing costs. System robustness, reliability, and ease of operation were also important design considerations.

Displayed in Table 1 are the principle design specifications used for the development of this cooler and some of the critical overall design characteristics resulting from these specifications. In general, the cooldown time and the cooling duration are the critical specifications that determine "flowrates, capacities, and sizes of the various cooler components. In most cases, BETSCE design characteristics and performance data were used as initial reference points for the design of this cooler.

Table 1. Cooler specifications & design characteristics

Design Parameter	Description
Cooldown Time from 60K to 10K	< 2 minutes
Cooling Duration Below 10 K with 100mW Load	> 10 minutes
Recycle Time	< 6 hours
Quantity of LaNiSn in high pressure sorbent bed	626 g
Hydrogen capacity, high pressure sorbent bed	8.01 g
Quantity of ZrNi in low pressure sorbent bed	251 g
Hydrogen capacity low pressure sorbent bed	1.87 g
Avg. hydrogen flowrate during cooldown from 60 to 10 K	0.1 g/s
Total hydrogen consumed during cooldown from 60 to 10 K	7.3 g
Coldhead mass	78 g
TSD mass	2.9 kg
Warm heat exchanger effectiveness, estimate	959.40
Cold heat exchanger effectiveness, estimate	95%
TSD heat exchanger effectiveness, estimate	95%

The simplified fluid schematic for this cooler is shown in Figure 2. Although fundamentally identical to Figure 1, this schematic includes a number of pressure transducers, service valves, and relief valves. An additional pneumatic valve was placed between the inlet and outlet lines of the JT cooldown loop to quickly vent gas from the high pressure side to the low pressure side prior to opening the low pressure sorbent bed. Also, a saran carbon coldtrap was incorporated into the recharge cycle between the high pressure sorbent bed and the tanks.

The physical layout of the cooler is shown in Figure 3. At the center of the upper level is the 15.2 x 30.5 cm cylindrical vacuum dewar that houses the cryostat. On left and right sides of the vacuum housing are the low pressure and high pressure sorbent beds, respectively. Underneath the sorbent beds are located two 1-liter tanks which hold the 10.3 MPA of hydrogen prior to a cooldown. Scattered over the remainder of the upper and lower levels area number of pneumatic valves, check valves, service valves, relief valves, and pressure transducers.

Sorbent Bed Design

The low pressure and high pressure sorbent beds circulate the hydrogen gas in a closed-cycle system and thermally compress it from a pressure of 266 Pa to 10.3 MPA. In general, powdered metal hydride materials such as $ZrNi$ and $LaNi_{4.8}Sn_{0.2}$ absorb hydrogen gas at low temperatures, and desorb it at higher temperatures and pressures. During chemical absorption, the materials reject heat and absorb mass. During resorption, the materials absorb heat and reject mass. From a design perspective, sorbent beds can be viewed as pressure vessels designed to transfer heat and mass to and from the powdered materials contained within them.

The overall design of the low pressure and high pressure sorbent beds are shown in Figure 4. As was previously described, the basic function of the low pressure sorbent bed is to maintain a vacuum of < 266 Pa on the collected hydrogen in the coldhead, thereby solidifying the hydrogen and reducing the temperature to below 10 K. To achieve this low pressure for the ten minute duration, 162 grams of powdered $ZrNi$ hydride alloy was used for an estimated reversible hydrogen capacity of 1.87 grams.

The primary functions of the high pressure sorbent bed are to absorb a large quantity of hydrogen in a short period of time during the initial cooldown at low pressure, and then to re-pressurize the tank by desorbing the hydrogen at high pressure. This sorbent bed uses 626 grams of powdered $LaNi_{4.8}Sn_{0.2}$ hydride for an estimated reversible hydrogen capacity of 8.01 grams.

In general, the designs of both sorbent beds are identical except for the outer diameter, inlet tube size, and the type of hydride material contained within. The primary housing for the powdered hydride material is a 22.9 cm long stainless steel cylinder with welded endcaps. To facilitate free molecular flow into the low pressure sorbent bed with minimal pressure drop, a 12.7 mm diameter inlet tube was selected instead of the 6.35 mm tube size selected for the high pressure bed. From the inlet tube, through the center of the sorbent bed, runs a 12.7 mm diameter sintered stainless steel 0.5 micron filter. This filter allows for gas flow into and out of the sorbent bed while preventing migration of the powdered metal hydride throughout the system. Pressed within the annulus between the filter and outer wall, occupying the same area as the powdered metal alloy, is a series of inter-locking copper fins. These fins are in direct contact with the metal powder and aid in the transfer of heat to and from the hydride material.

Wrapped around the stainless steel housings of the sorbent beds are thick aluminum sleeves. Along the base of these sleeves are drilled holes for insertion of 500 W rod heaters. During gas absorption, the aluminum sleeves help to draw the generated heat from the powdered metal alloy thereby minimizing temperature rise of the hydride material. During resorption, the sleeves enable more uniform heating of the sorbent beds.

Surrounding both of the sorbent beds are thin stainless steel tubes supported at either end by three small set screws. These tubes serve both as a radiation shield and as a means for thermally isolating the sorbent beds from the mounting plate. Gas-gap thermal switches, similar to those used in BETSCE,[2] would replace these stainless steel tubes in a flight system.

Cryostat Design

The overall cryostat assembly is depicted in Figure 5. The basic structure of the cryostat is provided by the almost 2.9 kg of solid aluminum comprising the thermal storage device (TSD)

and radiation shield. This aluminum structure was designed to be maintained at 60 to 80 K by means of a liquid nitrogen cooling loop operated near the triple point, and its large mass is meant to buffer the system from the high heat flux present during a rapid cooldown from 60 to 25 K. This uniform temperature TSD would be replaced by a segmented TSD for a flight system. The segmented TSD serves as a single stream regenerator, and results in a > 50°/0 reduction in TSD mass.

The liquid nitrogen cooling loop consists of five cylindrical canisters connected in series which are directly inserted into the TSD. To facilitate the inclusion of two saran carbon coldtraps, a system bakeout heater, and the liquid nitrogen cooling assembly, a series of eight 1.9 cm diameter by 6.35 cm long clamps were machined directly around the circumference of the TSD.

At the top and bottom ends of the TSD, around the circumference, is machined a spiral groove in which a 3.2 mm stainless steel tube is epoxied in place. This tube in close thermal contact with the aluminum TSD makes up the 2.49 m of TSD heat exchanger and connects the warm and cold heat exchangers.   Floating freely between the TSD heat exchanger and outer radiation shield of the cryostat, the warm and cold heat exchangers are thermally isolated from the 60 to 80 K cold sink. Although not explicitly shown in Figure 5, the JT expander is located at the end of the cold heat exchanger and is also free floating.

At the bottom of the cryostat, within the center cavity of the TSD, is located the coldhead and low pressure vent tube. Supply and return lines to the coldhead pass through small holes in the side of the TSD from opposite sides. The low pressure vent tube is 6,35 mm OD, .889 mm wall, stainless steel tubing thermally and structurally attached at the top of the TSD and coiled to a length of 38.1 cm to minimize heat leakage. Upon exiting the TSD, the vent tube transitions to 12.7 mm diameter tubing to minmize pressure drop and to provide a rigid support for the cryostat within the vacuum housing. The total length of 12.7 mm diameter tubing between the TSD and the outer vacuum housing is approximately 26.7 cm, Estimated conduction parasitic along the low pressure vent tube between the vacuum housing and TSD and between the TSD and cold head are 0.5 W and 12 mW respectively. Radiation parasitic between the coldhead and TSD are estimated at 4 mW.

Coldhead. The primary function of the coldhead is to collect and retain the liquid/solid hydrogen used for cooling the applied heat load. In designing the coldhead, emphasis was placed in the following areas: (a) minimizing thermal mass to reduce gas consumption and thus sorbent bed size, (b) improving conductivity between the collected hydrogen and the applied heat load, (c) developing a phase-separation and wicking mechanism to improve liquid and solid hydrogen retention, and (d) maintaining structural integrity at operating pressures up to 11 MPA.

Figure 6 illustrates the overall design of the cold head. The main body of the coldhead is a 2.54 x 2.54 cm cylindrical cup machined from beryllium copper with a wall thickness of .381 mm. As shown in Figure 4, the beryllium copper top cap is conical in shape with one inlet and two outlet ports. Pressed inside the main body of the coldhead are eight, 3.18 mm thick, sintered OFHC copper disks. These disks provide the wicking necessary to retain the liquid hydrogen and also provide an excellent heat path from the center of the coldhead to the outer shell.

In addition to the passive ticking provided by the sintered medium, it is also desirable to prevent liquid in the coldhead from being blown out by the incoming gas-liquid mixture. To alleviate this problem, gas-liquid phase separation was incorporated in the coldhead design. The basic principal is illustrated in Figure 7. By placing holes at specific positions in the sintered metal disks, it is possible to induce a helical flow. While the gas phase follows the helical path provided by the holes, the liquid phase is thrown out radially into the wicking medium where it is retained by capillary forces.

Heat Exchangers. Within the JT loop of the cryostat are two high-effectiveness counterflow soldered-tube heat exchangers. During a quick cooldown, these heat exchangers function as recuperators which extract the heat from the high pressure incoming gas by using the low temperature, low pressure, exhaust gas from the coldhead. In addition to minimizing pressure drop and maximizing effectiveness, size and ease of fabrication were also important design considerations.

The warm heat exchanger consists of seven 1.59 mm OD stainless steel tubes soldered together in the pattern shown in Figure 8. Through the center tube flows the high pressure incoming hydrogen gas at predicted temperatures of 300 to 95 K. Twisting around the center tube are six outer tubes which carry the low pressure exiting hydrogen gas at predicted temperatures of 50 to 280 K. The overall length of the heat exchanger is 2.41 m. Once soldered together, the warm heat exchanger was coiled into a 10 cm diameter helix.

The seven tubes of the cold heat exchanger are .813 mm OD stainless steel tubes soldered together in the same configuration as the warm heat exchanger. High pressure hydrogen gas from the TSD heat exchanger enters the center tube of this heat exchanger at an estimated temperature of 65 K and leaves at approximately 48K. Exiting hydrogen gas from the coldhead enters the six outer tubes of the cold heat exchanger, passes through the low pressure side of the cold heat exchanger, and enters the six outer tubes of the warm heat exchanger. The total length of the cold heat exchanger is 1.78 m.

Joule-Thomson Porous Plug. The design of the expansion device used to produce the Joule-Thomson (J-T)effect in this cooler was significantly influenced by the desire to reduce the cooler's sensitivity to contamination while also maintaining the necessary system performance. Instead of conventional orifice or capillary tube methods, a sintered metal porous plug was chosen to induce the desired pressure drop and set the required flowrate. A schematic of the J-T assembly is shown in Figure 9.

The actual porous plug is a 3.18 x 3.18 mm, commercially available, encapsulated flow restrictor, available over a wide range of standardized flow rates. During assembly, the flow restrictor is pressed into a machined stainless steel housing. On top of the flow restrictor is pressed a 0.5 micron sintered stainless steel cup filter with an available surface area of approximately 0,322 in^{A}2. Surrounding both the filter and flow restrictor is an all-welded 6.35 mm diameter stainless steel housing. The total length of the assembly is 2.86 cm.

PERFORMANCE PREDICTIONS

Sorbent Bed Performance

Based on experimental sorbent bed data from BETSCE and from previous material cycling and isotherm studies, it is possible to make accurate performance predictions for both the low pressure and high pressure sorbent beds. Based on the design margins for both heat removal and hydrogen absorption, it is also expected that performance during absorption will not significantly deviate from previous experimental data. Shown in Figure 10 are the predicted temperature and pressure profiles for both sorbent beds for the entire six hour cycle from initial cooldown to final tank recharge based on BETSCE test results.[2]

Cooldown Performance

Using experimental test results from previous proof-of-principal and BETSCE cooldown data, it is possible to predict the cooldown performance of this system. While the heat exchangers, ˉTSD, JT and sorbent beds are sized for a cooldown flow rate comparable to

'' BETSCE flowrates (approx. 0.1 g/s), the coldhead size and mass are significantly less than that of BETSCE. With this in mind, cooldown time is expected to be slightly faster for this cooler. However, cooling duration below 10 K is predicted to be less than that for BETSCE because of the reduced sorbent bed capacity margins. As an example, a typical cooldown curve for BETSCE is shown below in Figure 11.

SUMMARY AND CONCL1JS1ONS

This cryocooler is the result of recent efforts at JPL toward the future development of space qualified, low-cost, long-life, high performance 10 K sorption cryocoolers. Novel ideas implemented in this design include a sintered copper cryogen wick with an induced phase separation mechanism, and a highly robust contamination resistant porous plug JT. Utilizing the same basic technology as the space qualified BETSCE, this laboratory model is designed to provide comparable performance at less than one tenth of the size and weight. By replacing many of the off-the-shelf technologies with components optimized for size and weight, future miniaturization of this type of cooler appears readily attainable. Performance characterization testing of this cryocooler is scheduled to begin in August, 1995. Future studies proposed for this test bed include cooler contamination and long-term cycling tests. Test results will benefit future designs of periodic and continuous 10 K sorption coolers.

ACKNOWLEDGE ENTS

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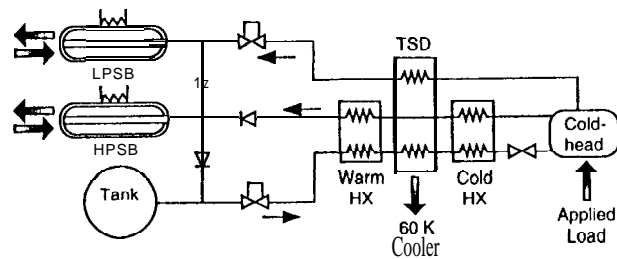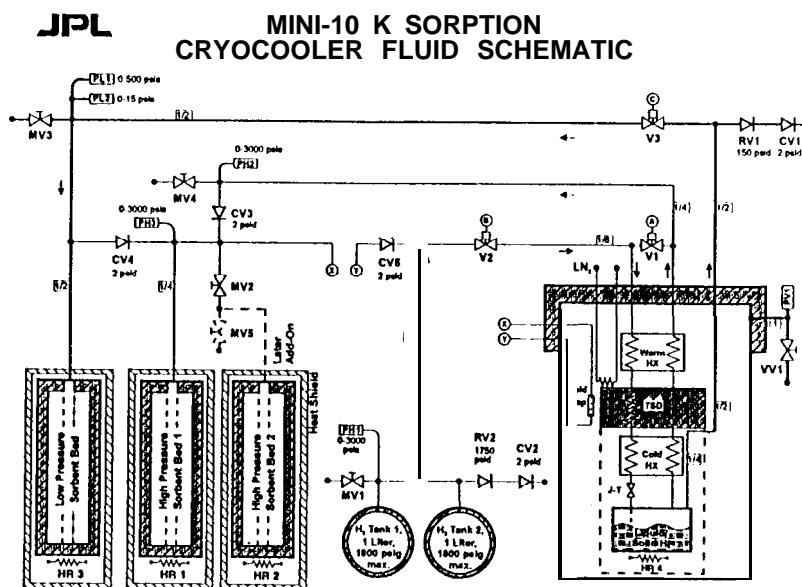
Fig. 1

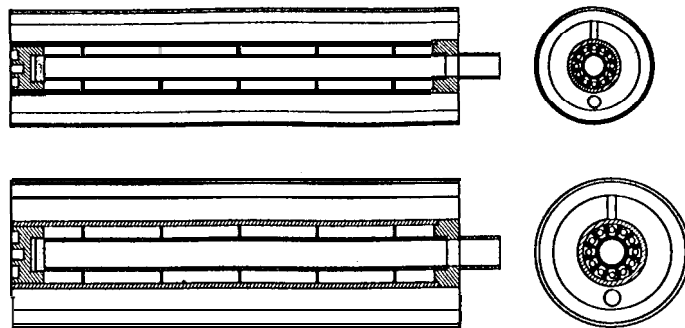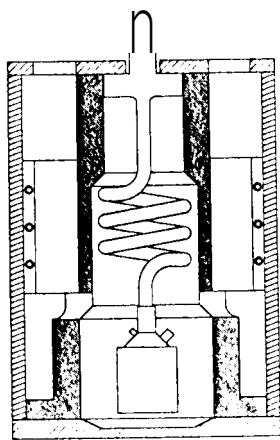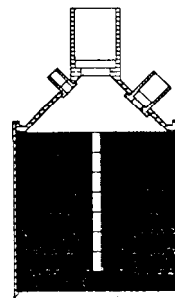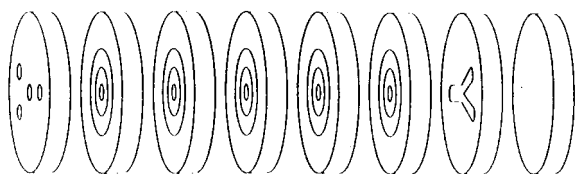**JPL**   **MINI-10 K SORPTION CRYOCOOLER FLUID SCHEMATIC**
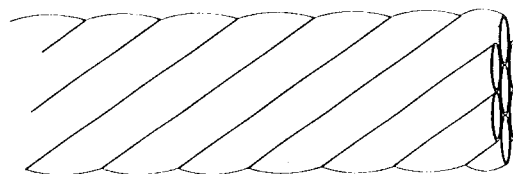
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